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SEARCH FOR RAPID FLUCTUATIONS IN LIGHT FROM THE CRAB NEBULA PULSAR*

D. HEGYI†
NASA Goddard Institute for Space Studies, New York, New York
R. NOVICK‡
Columbia Astrophysics Laboratory, Physics Department, Columbia University
AND
P. THADDEUS
Goddard Institute for Space Studies and Columbia Astrophysics Laboratory
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ABSTRACT

Observations have failed to reveal fluctuations in the light from the pulsar NP 0532 on a time scale from about 3×10^{-5} to 1×10^{-8} sec.

A report of optical coincidences (Porter, Jennings, and O'Mongain 1969) from the direction of the Crab Nebula has led us to study the intensity of the pulsar NP 0532 on a very short time scale. Although background events produced by cosmic-ray showers have so far prevented a detailed study of the pulse structure of NP 0532 down to the short time delays warranted by the apparatus, our initial observations can still be used to rule out extreme fluctuations in the pulsar light which would not appear in the time-averaged pulse structure studied by most observers. Ögelman and Sobieski (1969) have recently made similar observations of NP 0532 without detecting any rapid variation in the pulsar intensity, but because they used a dichroic filter for a beam splitter, their results apply only to coincidences between photons of different wavelengths. Anderson, Crawford, and Cudaback (1969) have also set limits on the short-term optical fluctuations of NP 0532 by pulse-height analysis of a single photomultiplier at the prime focus of the Lick 120-inch reflector. Five photoelectrons were apparently required to produce a pulse that could be distinguished with certainty from that of a single photoelectron. Thus the technique of these authors is inherently insensitive at short resolution times, since the probability of such an event is proportional to the fourth power of a small number.[1] Although their results are more sensitive than ours on a scale of $\sim 10^{-4}$ sec because of the large collecting area of the 120-inch telescope, they are much less sensitive than ours on a scale of 10^{-8} sec.

Our observations were made on the nights of 1969 April 18/19 and 19/20 with the 24-inch reflector of the New Mexico State University on Magdalena Peak and the coincidence circuitry shown in Figure 1. Light from an 8″ or 16″ aperture located at the Cassegrain focus of the telescope was collimated and split into two beams of nearly equal

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† National Research Council Postdoctoral Research Associate.

‡ Alfred P. Sloan Research Fellow.

[1] In the absence of rapid fluctuations the probability per 33-msec period of NP 0532 of a five-photoelectron event is $P_5 \sim n^5(\Delta\tau/\tau)^4/4!$, where $\tau \approx 1.5$ msec is the length of the main light flash, $\Delta\tau$ is the resolution time, and n is the number of photoelectrons detected per period. Taking the Lick value $n \approx 50$, with $\Delta\tau \approx 10$ nsec, yields $P_5 \sim 10^{-14}$.

intensity by a multilayer neutral-beam divider. Each beam was then detected by an Amperex 56DVP phototube having a 2-nsec rise time and peak sensitivity at 4000 Å. After conventional stages of amplification and discrimination, pulses from one phototube were used to start a time-to-amplitude converter (TAC), which was subsequently stopped by pulses from the second tube via a 60-nsec delay line. Pulse-height analysis of the TAC output yields the delayed-coincidence spectrum (i.e., the autocorrelation function) of the intensity of the observed light. Photoelectrons that are produced simultaneously yield counts in the 60-nsec (prompt) channel. The remaining channels correspond to various delays between the photoelectrons.

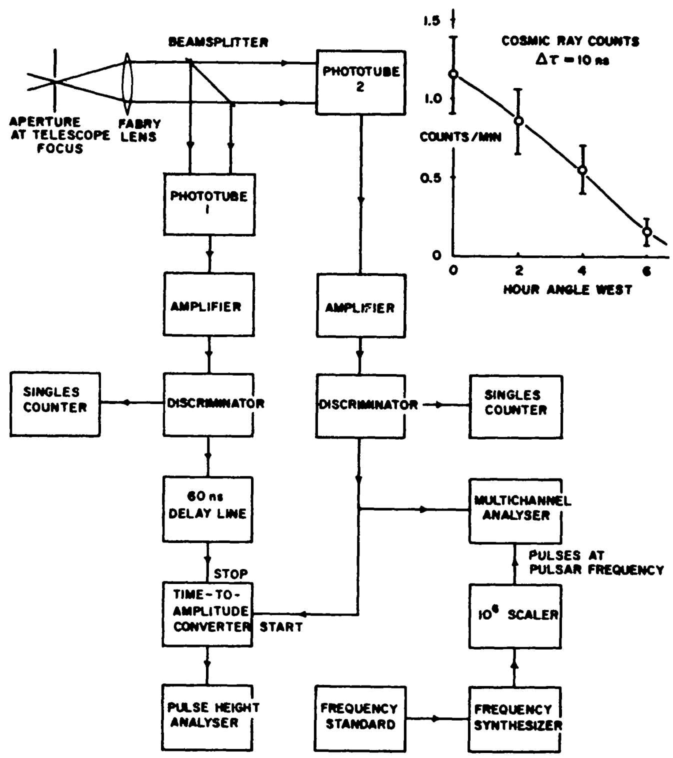

FIG. 1.—Coincidence circuitry. Cosmic-ray events as a function of hour angle are shown in the inset

Since only $\sim$24 square seconds of arc of the surrounding nebula contribute on the time average as much light as the pulsar itself (Oke 1969), it is desirable to use a small-focal-plane aperture. However, this greatly increases the difficulties of acquiring and offset guiding on an object of sixteenth magnitude, which to the eye is invisible in a 24-inch telescope. To assure ourselves that the pulsar was actually being observed, we therefore monitored one channel of the coincidence circuit with a multichannel analyzer synchronized to the local pulsar frequency, using for this purpose a frequency synthesizer and 10^6 scaler, as indicated in the lower right-hand corner of Figure 1. The characteristic double pulse of NP 0532 could be seen after only 10–20 sec of integration. Since we discovered that guiding for an indefinite period was relatively easy with apertures of 8″ and 16″ diameter but difficult for 4″ diameter, we confined our observations to the two larger aperture sizes.

Let $s_1(t)dt$ or $s_2(t)dt$ be the probability of arrival of a pulse in channel 1 or channel 2 within the interval dt at time t, and let $c(\Delta\tau,\tau,t)dt$ be the corresponding probability for a coincidence of two pulses within a time interval of width $\Delta\tau$ centered on a time delay τ.

We will call s_1 and s_2 the instantaneous pulse rates and c the instantaneous coincidence rate. It should be noted that τ refers to the time delay prior to the 60-nsec delay line. On all time scales longer than ~1 nsec, s_1 and s_2 will be proportional to the optical intensity of the pulsar, but they cannot possess structure on a shorter scale, because of the finite response time of the photomultipliers. Also, because of the dispersion of the terrestrial atmosphere, the intensity of the pulsar light received by the telescope is unlikely to possess any structure on a scale much shorter than 1 nsec. The quantities directly measured by our counters are the time integrals of s_1, s_2, and c over a run, which we will denote by the corresponding capital letters S_1, S_2, and C.

Data for our two best runs, with the TAC on its shortest full scale of 100 nsec, are summarized in Table 1. C_{obs} is the coincidence count registered in a 10-nsec interval centered on the prompt peak ($\tau = 0$). The next column, headed C_{cr}, lists the number of counts expected from cosmic-ray showers striking the phototube glass faceplates. This number is obtained from independent observation of the cosmic-ray coincidence rate as a function of the orientation of the telescope and attached apparatus; the results are summarized by the inset in Figure 1. The dependence on telescope orientation of the cosmic-ray counts is simply a consequence of the varying cross-section of phototube glass exposed to the showers. No significant contribution to the singles counts S_1, S_2 is made

TABLE 1

SUMMARY OF DATA FOR $\Delta\tau = 10$ nsec

Date and Time (1969 U.T.)	Length of Run and Mean Hour Angle	Aperture (seconds of arc)	S_1	S_2	C_{obs}*	C_{cr}	C_b	C_p(min)	C_p†
April 19, 3^h0^m.....	40 min, $4^h.5$ W.	8	2.26×10^5	3.79×10^5	12.0 ± 3.5	17.0 ± 5.8	0.35	0.11	< 8.3
April 20, 3^h30^m....	30 min, $5^h.0$ W.	16	0.86×10^6	1.17×10^6	20.0 ± 4.5	9.9 ± 3.9	5.6	0.08	<16.5

* Uncertainty is 1 standard deviation.

† These limits correspond to 2 standard deviations.

by the cosmic rays, but we note from Table 1 that they account for all or a large fraction of the observed coincidences. However, $C_{obs} - C_{cr}$ sets an upper limit to the coincidences produced by the pulsar and all sources of background counts, which, when the relative contributions of pulsar and background are evaluated, in turn imposes quite restrictive limits on rapid optical fluctuations of NP 0532.

Background counts can be produced by light from the Crab Nebula, the north following star about 5″ from NP 0532, the night sky, and the phototube dark current. The relative intensities of the main pulse, the interpulse, and the nebula adjacent to NP 0532 have been measured by Oke (1969). Our first run (8″ aperture) was made under photometric sky conditions, and the contribution of the night sky to the background was negligible. For this run, however, one-third of S_1 and S_2 was due to dark current, in contrast to the second run, when, because of the larger aperture (16″), only one-tenth of the singles counts was due to dark current. During the second run, however, there was some contamination by moonlight, which may account for the fact that, per unit aperture area, the singles counting rates were then about twice those during the first run. In analyzing the second run we have made the most unfavorable assumption, namely, that the entire increase in counting rate over the previous run was due to moonlight. For both runs we have assumed that the north following star, the mean intensity of which is comparable to that of the pulsar (Baade 1942), lay within the aperture and thus contributed to the background. Finally, taking all these sources of background counts into consideration, we find that the fractions of singles counts due to background, main pulse, and interpulse during the first run are, respectively, $f_b = 0.84$, $f_m = 0.115$, and $f_i = 0.046$. During the second run the corresponding figures are $f_b = 0.96$, $f_m = 0.025$, and $f_i = 0.010$.

These quantities, together with knowledge of the time-averaged pulse structure of NP 0532, then allow calculation of the mininum number of chance-coincidence counts expected from the pulsar plus background. The total number of coincidences registered during the run is given by

$$C(\Delta\tau,\tau) = \Delta\tau \int_{\text{run}} \langle s_1(t)\rangle \langle s_2(t-\tau)\rangle dt\,, \tag{1}$$

where $\langle s_1(t)\rangle$ and $\langle s_2(t)\rangle$ are the instantaneous rates averaged over the typically 10-nsec resolution time $\Delta\tau$. At zero time delay it follows directly from equation (1) and the Schwarz inequality that, for fixed singles counts S_1 and S_2, steady light yields the lowest number of chance coincidences over a run of fixed duration. If we now imagine the time-averaged pulse structure of NP 0532 to consist of a rectangular main pulse and a rectangular interpulse, this argument shows that the lowest number of coincidence counts is obtained when no short-term pulse structure exists, i.e., when the time-averaged and instantaneous pulse rates are identical. Specialized to this model of the pulse structure, with 1.54 msec for the width of the main pulse and 3.03 msec for the width of the interpulse, equation (1) yields, for the background coincidences C_b and the minimum number of pulsar coincidences C_p(min),

$$C_b = [f_b^2 + 2f_b(f_m + f_i)]S_1S_2\Delta\tau \tag{2}$$

and

$$C_p(\text{min}) = (21.5f_m^2 + 10.9f_i^2)S_1S_2\Delta\tau\,, \tag{3}$$

where we include the cross-terms between background and pulsar in the background counts. The eighth and ninth columns of Table 1 list C_b and C_p(min) calculated from these expressions, while the last column of the table gives the maximum number of pulsar coincidence counts allowed by observation, that is, $C_p = C_{\text{obs}} - C_{\text{cr}} - C_b$. The ratio of C_p to C_p(min) can now be used to set a limit to rapid fluctuations in the pulsar light on time scales as short as 10 nsec.

Suppose, as an idealized case, that the main pulse and interpulse of NP 0532 consist of a train of sharp random pulses of fixed length τ_p, mean separation τ_s, and equal intensity—the situation illustrated in Figure 2, *a*. It follows from equation (1) that the number of coincidence counts produced by such a train on a time scale much shorter than τ_p is greater by a factor τ_s/τ_p than the number produced by a steady source at the same mean intensity. Thus, in the notation of Table 1, $\tau_s/\tau_p = C_p/C_p(\text{min})$, and from the first and second runs we derive, respectively, the upper limit $\tau_s/\tau_p < 76$ and the upper limit $\tau_s/\tau_p < 68$. These limits apply over the entire range of τ_p from $\sim 10^{-5}$ to 10^{-8} sec. The limit $\tau_s/\tau_p < 68$ is indicated by *A* in Figure 2, *b*.

A slightly more restrictive limit is imposed on τ_s/τ_p, but one confined to a smaller range of τ_s, when the TAC is set on a longer time scale. Figure 2, *c*, shows the result of pulse-height analysis of a 15-min observing run with a 16″ aperture and the TAC on its maximum range of 30 μsec. Here each time bin $\Delta\tau$ is about 140 nsec wide, and the observed counts are nearly all due to the nebula and pulsar rather than to cosmic rays, since few particles in a shower are delayed by as long as 6 μsec. (No counts were recorded for delays less than 6 μsec on this TAC setting, because of malfunction of an initial group of channels in the pulse-height analyzer.) We note that the characteristic flat autocorrelation function of steady light is observed. Because of the relatively large aperture, however, only a small fraction ($\sim$1 percent) of the observed counts can be attributed to the pulsar itself, and again we can obtain only an upper limit to $C_p/C_p(\text{min}) = \tau_s/\tau_p$. From analysis of the counts shown in Figure 2, *c*, we find this to be $\tau_s/\tau_p < 52$, which holds over the range of τ_p from roughly 3×10^{-5} to 10^{-7} sec. This is the upper limit marked *B* in Figure 2, *b*.

The foregoing data on τ_s/τ_p can also be used to set an upper limit to the amplitude of a single sharp ($\tau \leq 10$ nsec) pulse superimposed on a slow (1.5 msec) unmodulated pulse, as was done by Anderson *et al.* (1969). Our result that τ_s/τ_p is less than 68 implies that the energy in a postulated single 10-nsec pulse must be less than 4.5×10^{-4} of the pulsar energy. By contrast, Anderson *et al.* (1969) set a limit of 0.1 on this quantity. Their further contention that less than 10 percent of the pulsar light is bunched into intervals of 10^{-7}, 10^{-6}, 10^{-5}, or 10^{-4} sec results in upper limits on τ_s/τ_p represented by the dashed line in Figure 2, *b*. Comparison of this limit with the limits *A* and *B* in the

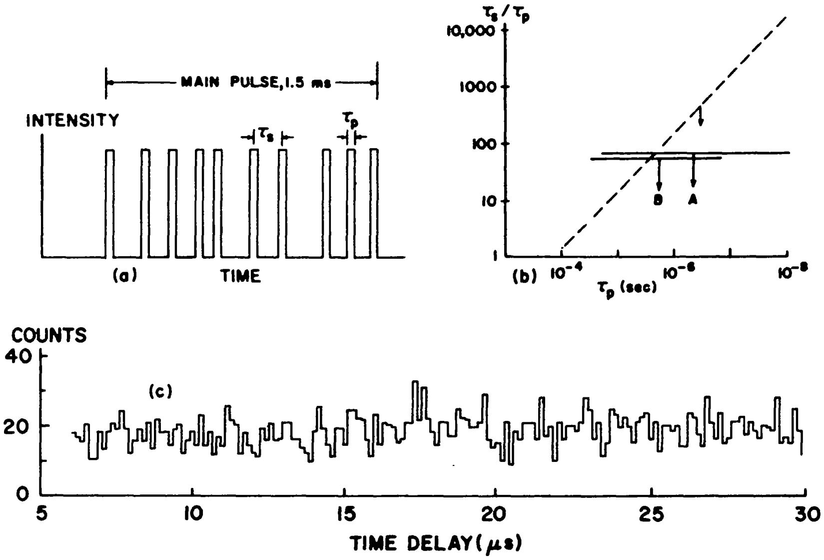

FIG. 2.—(*a*) Model of pulse structure; (*b*) upper limits on τ_s/τ_p; (*c*) coincidence counts versus time delay for a 15-min run taken with a 16″ aperture at 4^h20^m U.T., 1969 April 20.

figure emphasizes the sensitivity of the dual-channel coincidence photometer on a very short time scale. For $\tau_p > 3 \times 10^{-6}$ sec, however, the 25-fold increase in collecting area of a 120-inch over a 24-inch telescope outweighs the advantage of this mode of detection, and the Lick observations set the lower upper limit to τ_s/τ_p.

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